

## CAN PROMINENCES FORM IN CURRENT SHEETS ?

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## ABSTRACT

Two-dimensional numerical simulations of the formation of cold condensations in a vertical current sheet have been performed using the radiative, resistive MHD equations with line-tied boundary conditions at one end of the sheet. Prominence-like condensations are observed to appear above and below an X-line produced by the onset of the tearing-mode instability. Cooling in the sheet is initiated by Ohmic decay, with the densest condensations occurring in the region downstream of a fast-mode shock. This shock, which is due to the line-tied boundary conditions, terminates one of the two supermagnetosonic reconnection jets that develop when the tearing is fully developed. This paper emphasizes the condensation properties of shock waves, which may trigger or considerably enhance the conditions for thermal condensations.

## I. 2D NUMERICAL SIMULATION

The initial condition is a vertical current sheet in both mechanical and thermal equilibrium, and the half-width and the height of the sheet are 0.15 and 4.0 in units normalized to the horizontal size of the box. The sheet magnetic Reynolds number is 120; and the ratios of radiative, diffusive and tearing time scales to the Alfvénic one are 20, 120, and 11, respectively. A symmetry condition is used in the center of the sheet, free-floating boundary conditions are fixed at the top and the right edges of the box, and line-tying conditions are used at the base. The initial plasma  $\beta$  outside the current sheet is 0.1 (Forbes and Priest 1983, Malherbe et al. 1984, Forbes and Malherbe 1986a,b).

We now present an order of magnitude model to investigate the thermal effects of hydrodynamic shock waves and explain their condensing properties in the solar corona.

## II. A SHOCK CONDENSATION MECHANISM FOR PROMINENCES

Consider a hot coronal equilibrium (subscript o quantities) described by:

$$0 = h\rho_o - \rho_o^2 Q(T_o), \quad (1)$$

where the wave heating term  $h\rho_o$  balances the radiative loss term

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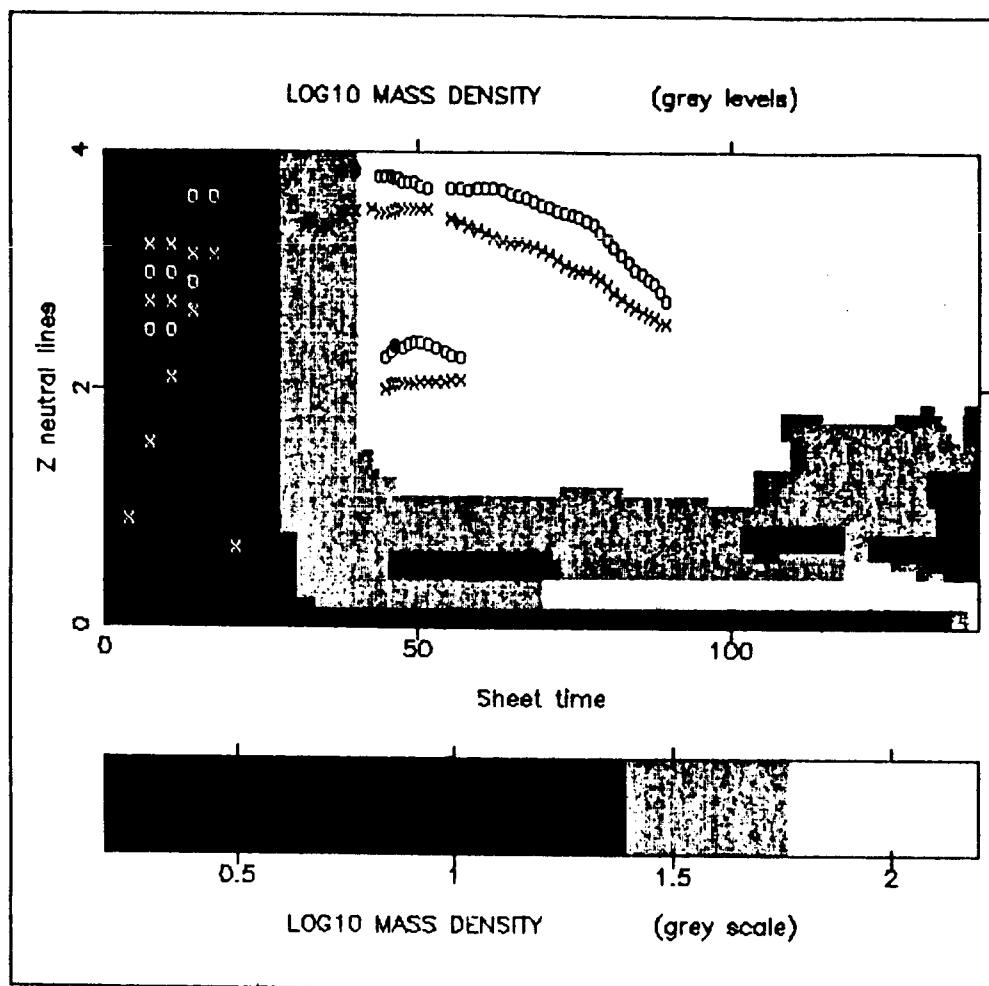


Figure 1. Time evolution of the mass density in the center of the sheet, together with locations of X and O magnetic lines. The time is in units normalized to the sheet Alfvénic time  $t_A$ . Two condensations separated by a more tenuous region appear.

$Q(T) = \chi T^\alpha$  given by Hildner (1974) as:

T(K)		$\chi$ (MKSA)	$\alpha$
$1.5 \times 10^4$ $8 \times 10^4$ $3 \times 10^5$	$T < 1.5 \times 10^4$	$1.759 \times 10^{-13}$	7.4
	$T < 8 \times 10^4$	$4.290 \times 10^{10}$	1.8
	$T < 3 \times 10^5$	$2.860 \times 10^{19}$	0
	$T < 8 \times 10^5$	$1.409 \times 10^{33}$	-2.5
	$T > 8 \times 10^5$	$1.970 \times 10^{24}$	-1.0

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Now perturb this equilibrium at constant gas pressure, incorporating conduction

$$\rho C_p (\partial T / \partial t) = h_p - \rho^2 Q(T) + k_o T^{5/2} (T_c - T) / L^2, \quad (2)$$

$$\rho T = \text{constant}. \quad (3)$$

$T_o$  is the hot initial temperature,  $k_o$  is a constant, and  $L$  is a typical thermal length-scale along a magnetic field line. Letting  $u = (T - T_o) / T_o$ , equations (1) to (3) reduce to

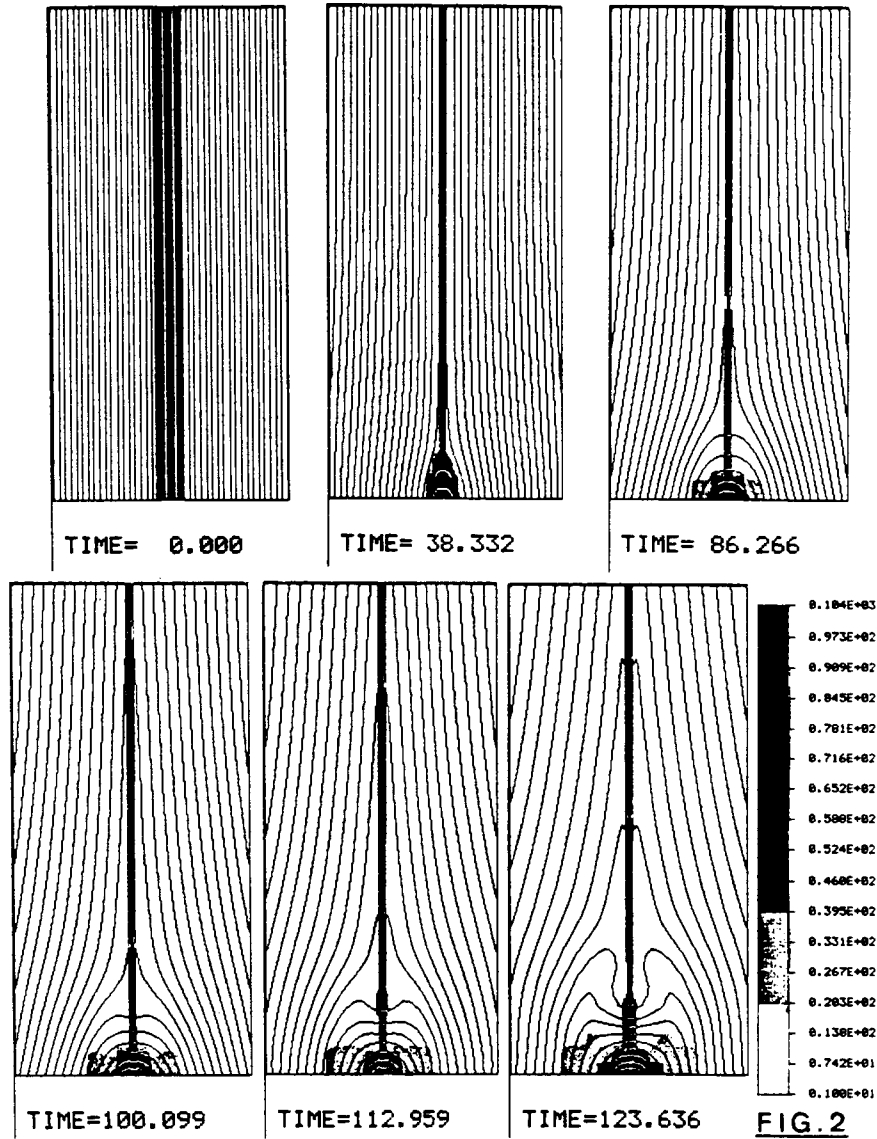


Figure 2. Magnetic field lines, together with the mass density (in grey levels) at different times. A strong condensation develops after  $t = 100$  at the top of the closed reconnected region. The dip in field lines is not caused by gravity (which is not included in the code), but by the force of the supermagnetosonic jet issuing from the reconnection site above.

$$\partial u / \partial t = -u [\tau_c^{-1} - \tau_R^{-1} (1-\alpha)] = -u/\tau,$$

where  $\tau_c = (\rho_o L^2 C_p) / (k_o T_o^{5/2})$  and  $\tau_R = (T_o C_p) / [\rho_o Q(T_o)]$  are the conductive and radiative time-scales. The hot equilibrium is stable when

$$\tau^{-1} = \tau_c^{-1} - (1-\alpha) \tau_R^{-1}$$

With no conduction ( $\tau_c = \infty$ ) this relation is always satisfied for  $\alpha > 1$  or  $T_o < 8 \times 10^4$  K. So a cold equilibrium is always stable and a hot one always unstable. With conduction, the equilibrium is stable when  $\tau_R/\tau_c > 1-\alpha$  and this is always the case when  $\alpha > 1$  (cold equilibrium). It may also be the case when  $\alpha < 1$  (hot equilibrium), if the following inequality is satisfied:

$$L < L_c = [k_o T_o^{7/2}]^{1/2} [\rho_o^2 Q(T_o) (1-\alpha)]^{-1/2}.$$

If  $L > L_c$ , the hot equilibrium becomes unstable.

Suppose now that a fast-mode MHD shock occurs in the reconnection jet, and let us examine the quantities  $\tau_R$ ,  $\tau_c$ ,  $\tau$ , and  $L$ , upstream (supersonic flow denoted by subscript u) and downstream (subsonic flow denoted by subscript d) of the shock. Because the magnetic field in the jet has almost been completely annihilated we can use the hydrodynamic jump relations. For a monatomic gas with  $\gamma = 5/3$ , these give

$$1 \leq \rho_d/\rho_u \leq 4.$$

Defining the compression factor across the shock as  $\chi = \rho_d/\rho_u$ , we have

$$V_u/V_d = \chi, \quad P_d/P_u = (4\chi-1)/(4-\chi), \quad T_u/T_d = \chi(4-\chi)/(4\chi-1).$$

From (4), we obtain

$$\begin{aligned} \tau_{Ru}/\tau_{Rd} &= \chi^{2-\alpha} [(4-\chi)/(4-1)]^{1-\alpha} \\ \tau_{cu}/\tau_{cd} &= \chi^{-7/2} [(4\chi-1)/(4-\chi)]^{5/2} \\ L_{cu}/L_{cd} &= \chi^{11/4-\alpha/2} [(4-\chi)/(4\chi-1)]^{7/4-\alpha/2}, \quad (\alpha < 1) \end{aligned}$$

At high temperatures ( $T > 3 \times 10^5$  K,  $\alpha < 0$ ) and in the absence of conduction, the shock decreases the radiative losses ( $\tau_{Ru}/\tau_{Rd} < 1$ ). However, at lower temperatures ( $T < 3 \times 10^5$  K,  $\alpha \geq 0$ ), it increases the radiation losses, and the cooling time becomes faster.

When the temperature is high ( $T > 3 \times 10^5$  K), the shock makes the triggering of a thermal instability more difficult in the presence of conduction ( $L_{cu}/L_{cd}$ ). But, when  $T \lesssim 2 \times 10^5$  K ( $\alpha = 0.9$ ), it is possible to have a thermally stable upstream ( $L < L_c$ ) and an unstable downstream ( $L > L_c$ ). This is the case when  $L_{cu}/L_{cd} > 1$  and when  $L_{cd} < L < L_{cu}$ . As one can see from Figure 3 this corresponds to a shock strength  $\chi$  smaller than 2 when  $\alpha = 0.9$ . Hence, under certain conditions (e.g. transition zone like temperatures) the shock may trigger

a thermal condensation, when conduction is included in the set of equations. The shock always triggers a condensation in the absence of conduction if  $\alpha < 1$ . This result is similar to that deduced by Fisher (1986) from his numerical experiments.

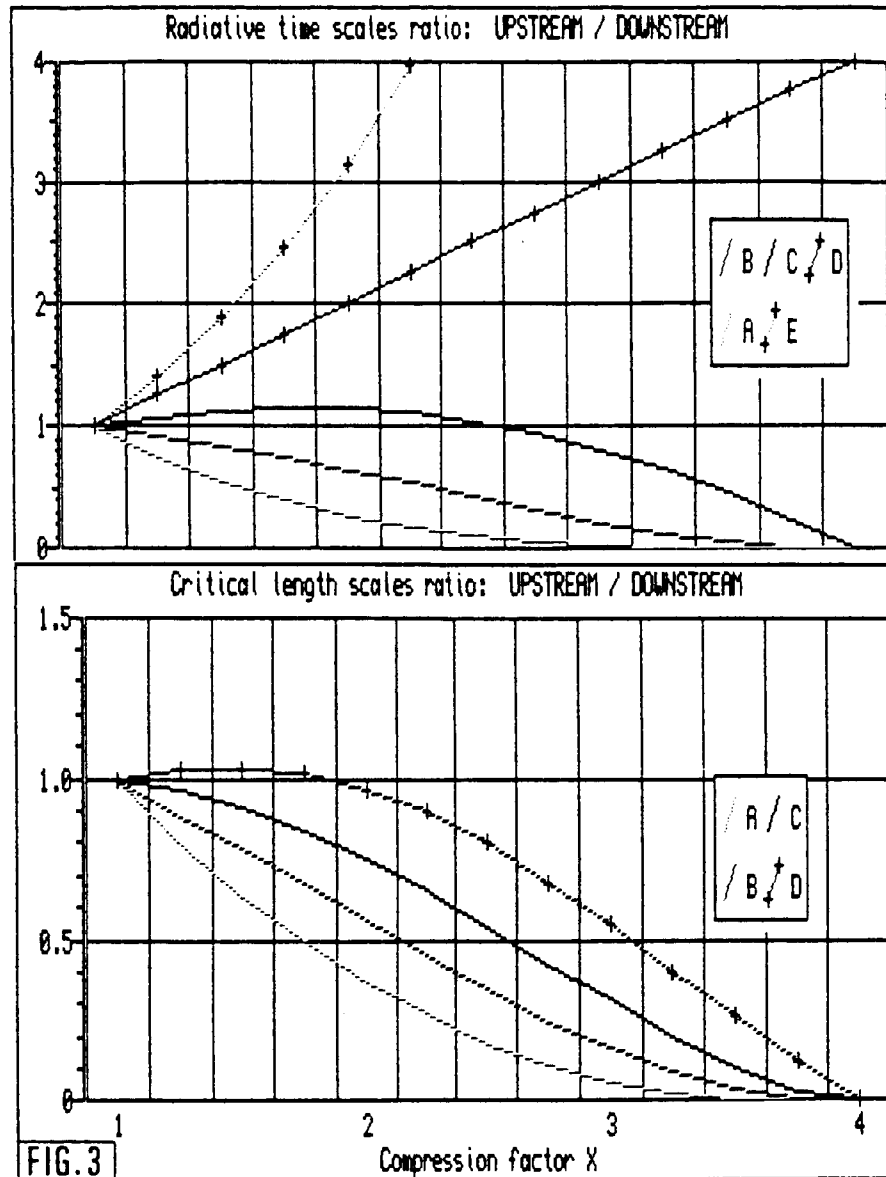


Figure 3, Top panel: The ratio  $\tau_{Ru}/\tau_{Rd}$  as a function of  $\chi$  for different values of  $\alpha$  (A: - 2.5, B: -1.0, C: 0.0, D: 1.0, E: 1.8), corresponding to different temperature ranges. Bottom panel: The ratio  $L_{Ru}/L_{Rd}$  as a function of  $\chi$  for different  $\alpha$  values (A: - 2.5, B: -1.0, C: 0.0, D: 0.9).

What is the effect of a shock at very low temperatures ( $T < 8 \times 10^4$  K and  $\alpha > 1$ )? In this regime, a cold flow is always thermally stable and the ratio of cooling times  $\tau_u/\tau_d$  may be expressed as

$$\tau_u/\tau_d = (\tau_{Ru}/\tau_{Rd}) [(\tau_{Rd}/\tau_{cd}) - 1 + \alpha][(\tau_{Ru}/\tau_{cu}) - 1 + \alpha]^{-1}.$$

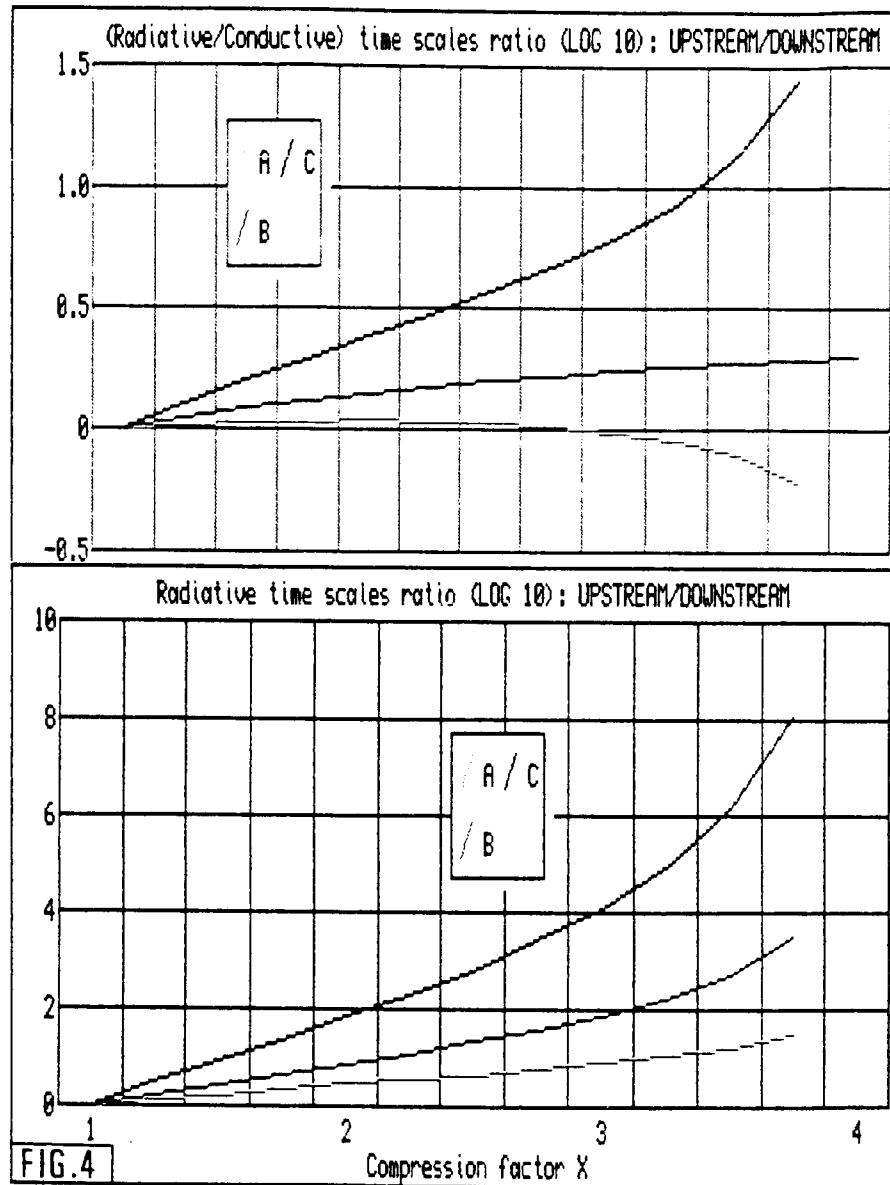


Figure 4. Top panel exhibits the quantity  $\text{Log}_{10} [(\tau_{Ru}/\tau_{cu})/\tau_{Ru}/\tau_{cd}]$  as a function of  $X$  and  $\alpha$  (A: 1.8, B: 3.5, C: 7.4). Lower panel represents the function  $\text{Log}_{10} [\tau_{Ru}/\tau_{Rc}]$  for the same  $\alpha$  values. The variations of the former quantity are almost negligible compared to the variations of the latter one, and consequently  $\tau_u/\tau_d \approx \tau_{Ru}/\tau_{Rd}$ . This ratio is much greater than 1, and shows that the presence of a shock at chromospheric like temperatures considerably enhances the radiative losses and the cooling time.

#### ACKNOWLEDGEMENTS

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